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THE ROLE OF UV-OPTICAL OBSCURATION IN STARBURST GALAXIES

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INTRODUCTION

The starburst phenomenon has been viewed as increasingly important since the recognition in the early 1980s that some galaxies have regions (either in their disks or confined to a small nucleus) in which stars are forming so rapidly that we must be seeing a transient event. Such starbursts populate samples of galaxies selected either for UV or infrared excess, and some have been found from IRAS source identifications that must be quite heavily obscured at optical wavelengths.

Many interpretations of the physical conditions in these objects and their stellar populations have relied on scaling from models of individual H II regions, and this certainly seems justified from the gross appearance of the optical spectra and IR spectral shapes. However, there are certain lines of evidence that such a straightforward interpretation may be misleading in these very large and luminous aggregates:

- Estimates of *extinction* obtained at various wavelengths disagree substantially, such that IR indicators give higher extinctions than those at shorter wavelengths. This indicates mixing of emitting and absorbing sources, and that there is no unique value of extinction to be applied at a given wavelength independent of knowledge of the source structure.
- Measurements of thermal emission confirm that many starbursts have a large amount of associated dust, but strong *optical emission lines* and *ultraviolet continua* are observed. Clearly a screen model for reddening is inappropriate, but the implications of coextensive obscuring matter and ionizing star clusters have yet to be satisfactorily worked out.

These observations showing that dust is present, but distributed in some complex way intermingled with the emitting stars, so that simple scaling of H II region models or analogs may give misleading results with regard to stellar ages or mass distributions and total luminosities. This proposal involved collection of complementary UV, optical,

and near-infrared data on a set of starbursts, with a preliminary analysis of models for more realistic internal structure.

UV AND OPTICAL DATA

A set of consistent spectral energy distributions has been generated for a sample of starbursts in galactic nuclei and disks, using the IUE archives and new ground-based optical and K-band data. The sample (Table 1) consists of the nuclei listed by Balzano (1983) or Devereaux (1989) that had observations available in the IUE archives as of early 1991.

IUE data handling: All IUE data were reprocessed using either the GEX Gaussian extraction program (Urry and Reichert 1988) or the newer optimal extraction software at the GSFC RDAF (Neill et al. 1991). GEX was used for those objects in which the UV intensity profile along the IUE large aperture major axis is pointlike, while the optimal procedure gives more reliable results when IUE resolves the UV light distribution. Both the resulting integrated spectra and cross-cuts in multiple wavelength bands were retained for analysis.

Optical imaging: Images in broad bands B,V,R,I, and narrow bands including redshifted $H\alpha$ emission were obtained with the 1.1-m telescope of Lowell Observatory. Absolute flux calibrations were done both with BVRI standard stars and spectrophotometric standards for the $H\alpha$ filters, to allow absolute comparison with the UV results.

Near-infrared imaging: Images for most of the sample objects were obtained in the K band (2.2μ) during a January 1990 run with the 1.3-meter telescope at Kitt Peak. The field size of 80 arcseconds was ample to allow accurate sky level measurements, so that absolute intensities should be reliable, and comfortable larger than the IUE aperture (Fig. 1).

UV-optical comparisons: The images allow production of spectral energy distributions covering exactly matched parts of each galaxy, so that, at the expense of possible added

light from older bulge stars in the redder bands, the resulting spectral shape refers to one spatially limited stellar population. The flux in each broad-band or emission-line image was summed over the region covered by the relevant IUE aperture, using a program written by then-undergraduate M. Cooper under support from this ADP grant. Errors in UV-optical flux ratios are frequently dominated by pointing uncertainties rather than intensity calibration uncertainties, so these were evaluated for each object by assessing the dependence of measured optical flux on assumed center location of the IUE aperture. Even though the center of the IUE aperture is often well specified along the “slit”, the pointing in the dispersion direction is uncertain at the few arcsecond level. In some cases, the uncertainties in matching optical and UV apertures lead to uncertainties $\pm 10\%$ in relative optical flux.

BROAD-BAND STARBURST SPECTRA

In addition to the observed continuum intensities from 1200 \AA to 2.2μ , corrected for foreground Galactic reddening using the Seaton (1979) prescription, information is available on the ionizing ultraviolet intensity intercepted by the gas in these systems. The $H\alpha$ intensity from the narrow-band images was corrected for contamination by the neighboring $[N \text{ II}]$ forbidden lines using spectroscopically known line ratios, and converted into a number of Lyman continuum photons using recombination theory. The far-UV intensities thus inferred fall well above any extrapolation of the directly observed stellar continuum longward of Lyman α . An example is shown in Fig. 2, the spectral energy distributions of NGC 1614 and 7714. The intensity of ionizing radiation is shown schematically as flat between the H^0 and He^+ ionization edges; the exact level is sensitive to the spectral shape of the ionizing star clusters, since what we can measure gives the total number of ionizing photons and not their total energy. The ionizing continuum is almost ten times stronger than the starlight just longward of this.

This is a refinement of the spectral argument for selective obscuration that formed

the motivation of this study. *It is a general property of starburst nuclei that the ionized gas is illuminated by more stellar UV radiation than emerges along the direct line of sight.* Furthermore, the reddenings derived by techniques using optical, UV, and IR indicators may disagree dramatically. These facts, along with an imaging demonstration of emission-line material seen around optically invisible IR sources (see Keel 1989), suggest a geometrical interpretation of obscuration in starbursts.

A SIMPLE MODEL: OBSERVABLES AND STARBURST STRUCTURE

A simple picture of star formation on distinct clouds illuminates many of the issues in the structure of starbursts. The density and typical filling factor may be estimated from recent CO interferometry (reported, for example, in IAU Symposium 146, "Dynamics of Galaxies and their Molecular Cloud Distributions", Paris 1990). The amount of starlight absorbed by dust in these clouds and the surrounding medium may be constrained by IRAS flux measures. Finally, the spatial extent and dust content of the gas surrounding the star-forming zone are given by emission-line images, which in many cases resolve the Strömgren volume, and by observed Balmer emission-line decrements.

These have been incorporated first into a two-dimensional model which allows relatively quick examination of the impact of such factors as compactness of the cloud configuration or typical shape of clouds on observables such as total IR or line emission, or escaping stellar UV continuum, for a fixed total star-formation rate.

In these models, a set of molecular clouds is distributed in a Gaussian configuration, and star clusters are formed near the cloud surfaces. Emergent rays are traced until they either leave the grid (generally at negligible intensity) or intercept another cloud. Each grid point not occupied by a cloud maintains a sum of UV intensities from all clusters to whose radiation the point is exposed, so that a grid of local UV intensity is maintained. This will be related to surface brightness in some recombination line;

in general the medium surrounding the clouds has measurable dust content, so that the details need to be fine-tuned to match specific objects. A set of models has been generated for fixed cloud number and rate of star formation, varying the size of the whole configuration relative to the cloud size and the form factor of individual clouds (circular vs. elliptical of various axial ratios).

Trends of global properties IR/blue ratio and relative emission-line intensity are shown in Fig. 3 for this two-dimensional case. Because full three-dimensional treatments still need to be run, these are best regarded as suggestive of scaling laws or applicable to very flattened bursts such as have been suggested for M82. In the two-dimensional limit, thermal IR emission from clouds heated by the young clusters increases for smaller configurations, while observed line emission decreases; note that the ratio of these may vary by a factor 10 as the size of the starburst region changes by a factor 5.

The existing model is still being developed. Future extensions, besides adding a third dimension to verify the scaling laws suggested from two dimensions, will include realistic spectral energy distributions for star clusters and evolution of both the stars and their coupling to molecular clouds.

Implications

These results begin to resolve some long-standing puzzles in understanding regions of intense star formation. In particular, given the IR-based evidence for strong extinction, why do we still see strong optical emission lines, and even continue to see flat UV spectra? The answer is that we see some of the ionizing star clusters directly (giving UV radiation with only slight reddening by the diffuse surrounding material), and we see emission-line material powered by the many “searchlight beams” escaping between more or less distinct molecular clouds from within the configuration, as well as by the clusters we can see directly. Thus diagnostics often used for the age or stellar population in H II regions, such as Balmer-line equivalent widths or UV/infrared flux

ratios, will be quite misleading in such an environment. The continuum and emission lines refer to different fractions of the overall stellar populations.

In addition to the range of properties covered by the objects in Table 1, statistical analysis can tell what the most typical diagnostic properties of starbursts are, and thus what a representative role for selective obscuration effects is. As a start, Gallimore (1990) has collected optical intensity and environmental data for a complete sample of IRAS galaxies in a Master's thesis with partial support from this grant. This material will be further used for analysis of the distribution of optical-IR ratios.

References

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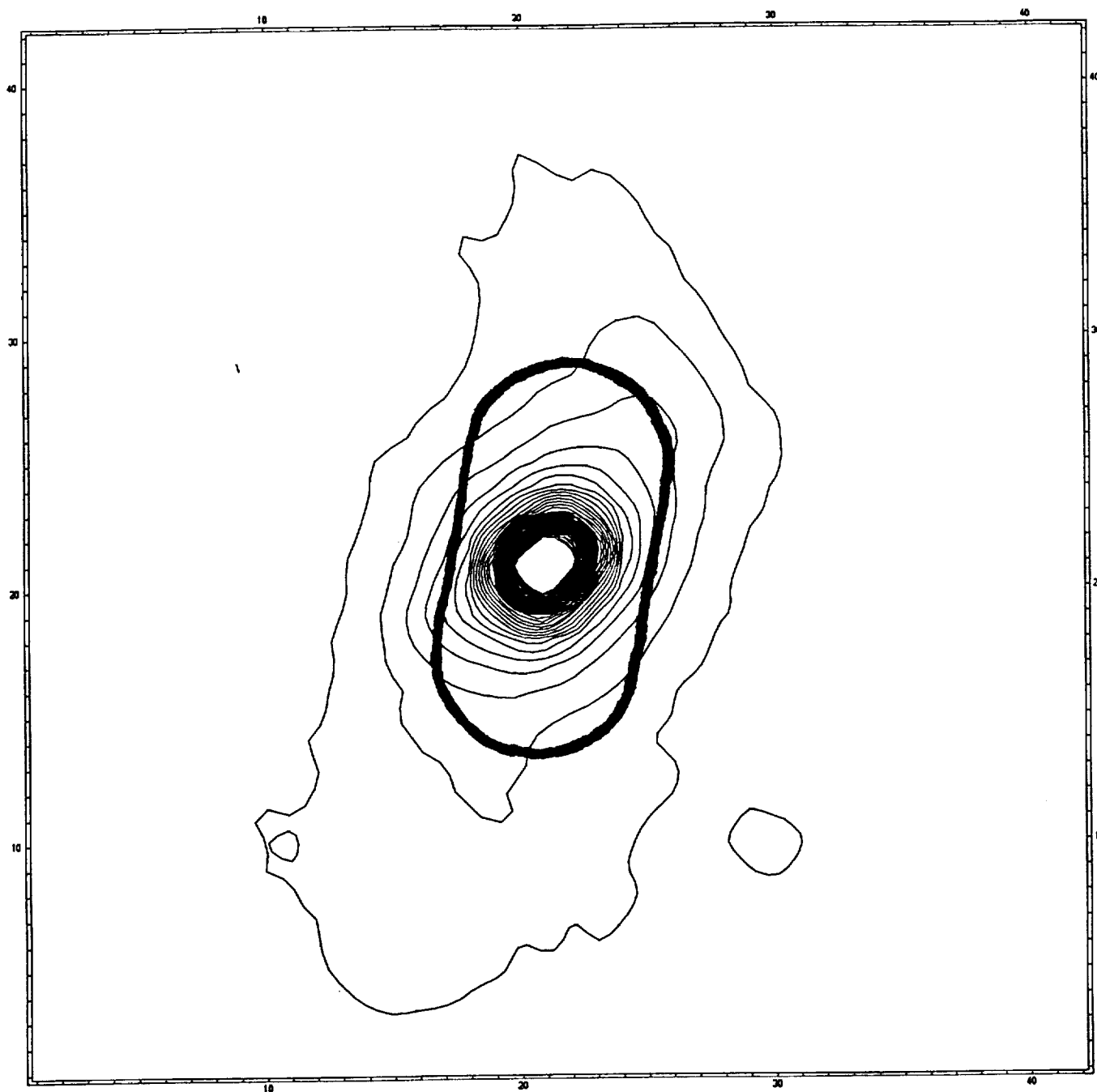
TABLE 1

Starburst nuclei - IUE and ground-based data

Galaxy	IUE Exposures	Other images
NGC 1614	SWP 25483	BVRH α IK
NGC 2782	SWP 23080,LWP 3416, LWR 5883	BVRH α K
NGC 2798	SWP 24699	RH α
NGC 3395	SWP 25465	BVRH α IK
NGC 3396	SWP 25485	BVRH α IK
NGC 3504	SWP 5661, LWR 4906	BVRH α IK
NGC 3690	LWR 15387,15394,SWP 13935,19341	BVRH α IJK
NGC 3991	SWP 19218	BVRH α IK
NGC 3995	SWP 07212, LWR 12534	BVRH α IK
NGC 6052	SWP 20119, LWR 1585	RH α
NGC 7714	LWR 03499	BVRH α IK
Mkn 357	SWP 18199	RH α

Figure 1. The IUE aperture (for observation LWR 3499) superimposed over a contour display of the *K*-band image from Kitt Peak. Most of the intensity is contained inside the IUE aperture, so that a reliable measurement of broadband spectral shape is possible.

n7714k[10:51,10:51]: NGC 7714 K 100sec #1 no guide star



contoured from 50. to 2000., interval = 50.
 NOAO/IRAF V2.9EXPORT KEEL@okra Fri 10:54:09 06-Sep-91

Figure 2. Spectral energy distributions for the nuclei of NGC 1614 and 7714. The Lyman-continuum flux is shown schematically as flat in F_λ ; its level will vary somewhat depending on effective stellar temperature. The high level of ionizing radiation compared to that seen directly from stars longward of Lyman α indicates a role for selective extinction; the less of the starlight is seen along the direct line of sight than by the whole volume of observable ionized gas.

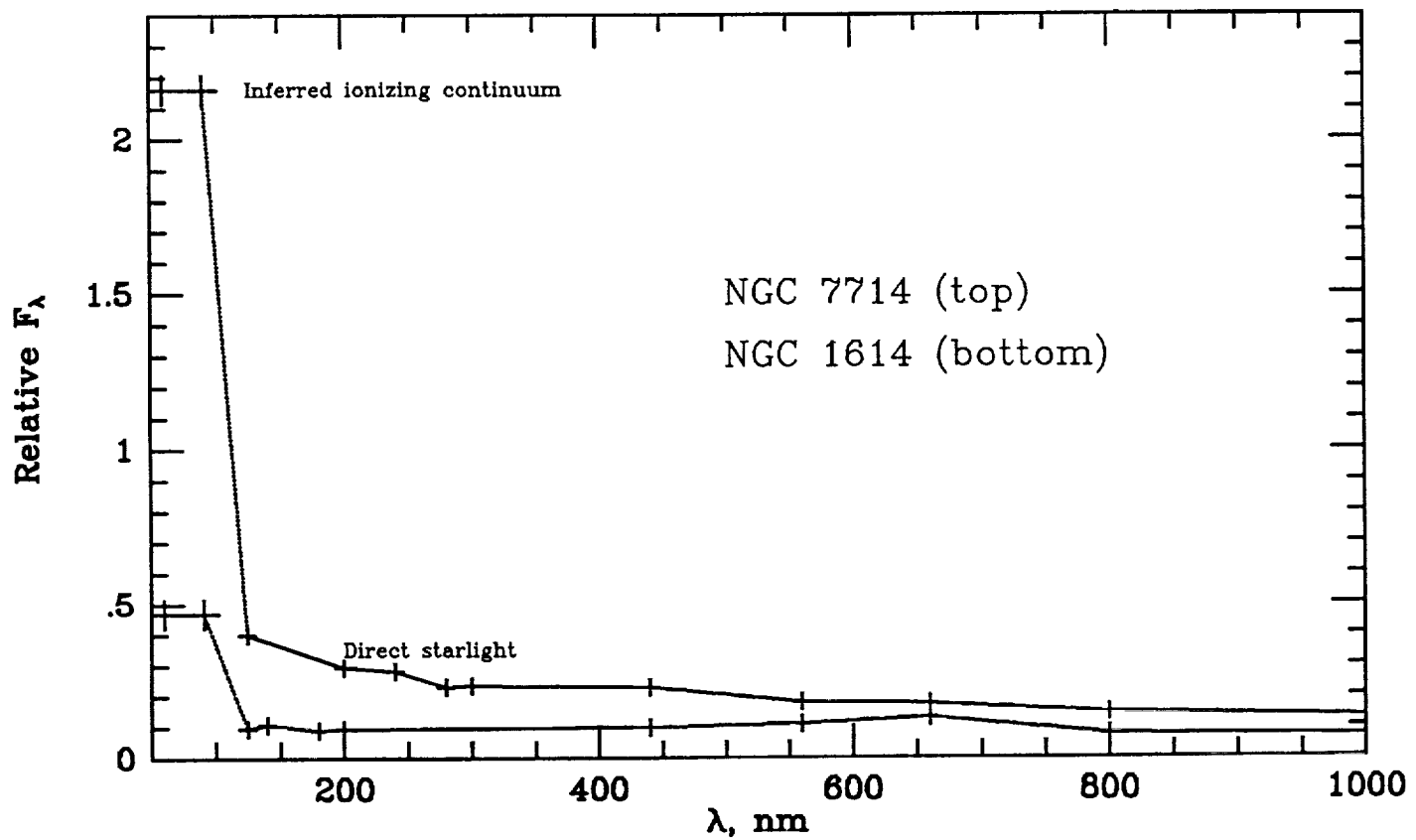


Figure 3. Behavior of far-infrared and emission-line luminosity of the 2-dimensional starburst model, each in arbitrary units, as a function of nucleus size compared to a typical cloud size. The FIR luminosity declines for less compact configurations, while the emission-line luminosity increases as more UV escapes to photoionize the gas. The range of emission-line intensities depicted here shows the variation with cloud aspect ratio (circular up to 5:1), while the FIR intensity is relatively insensitive to cloud shape.

